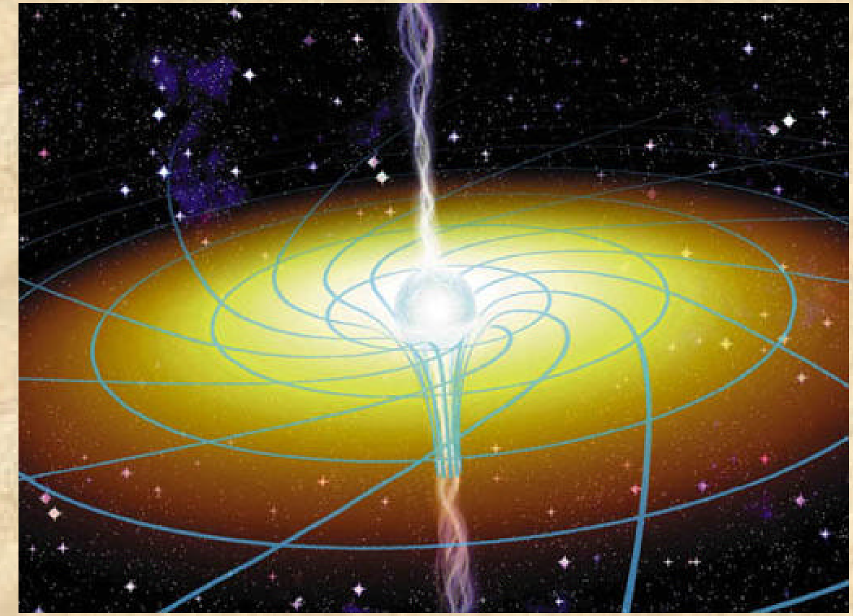
TOWARDS NEW TESTS OF STRONG-FIELD GENERAL RELATIVITY

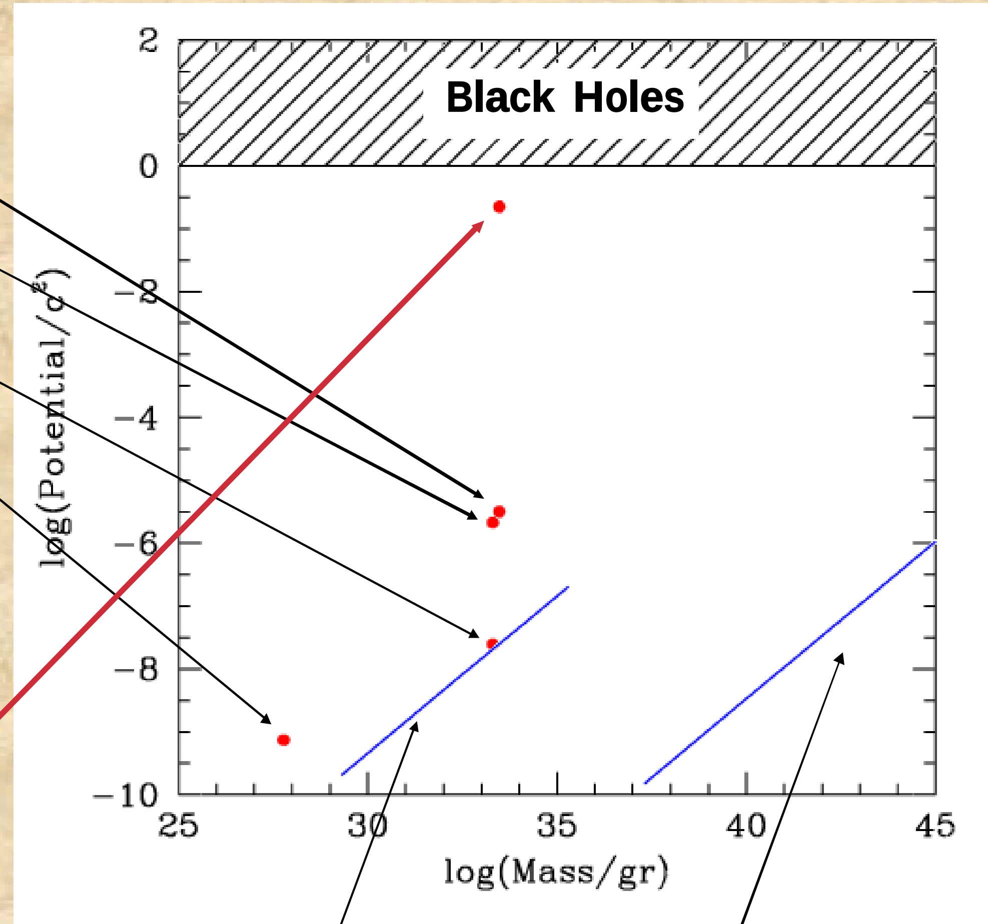


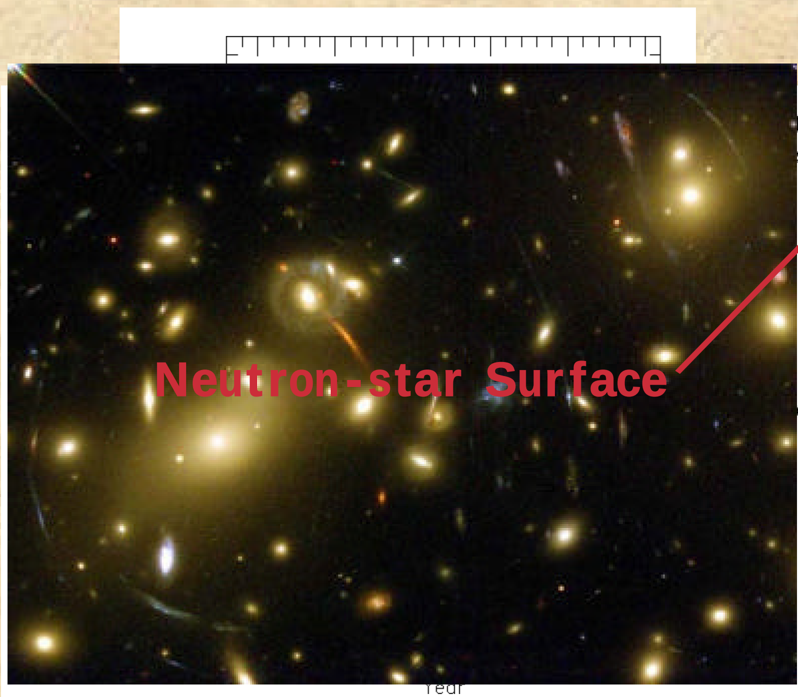
DIMITRIOS PSALTIS
University of Arizona

with SIMON DEDEO - Princeton University

TESTS and PROBES OF GENERAL RELATIVITY

- Hulse-Taylor Pulsar
- Deflection of Light
- Shapiro Time Delay
- Precession of Mercury
- Terrestrial Experiments



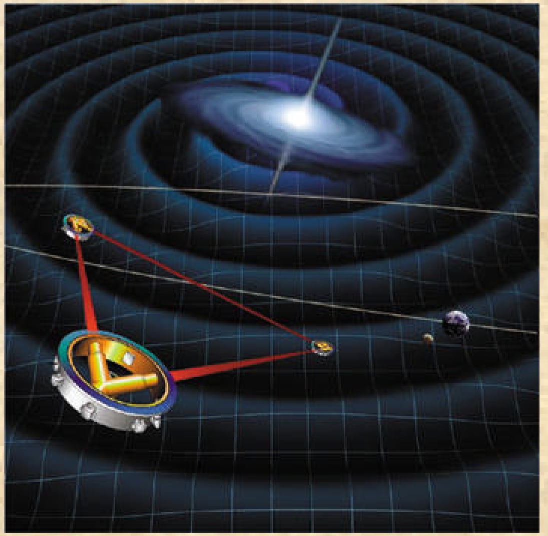


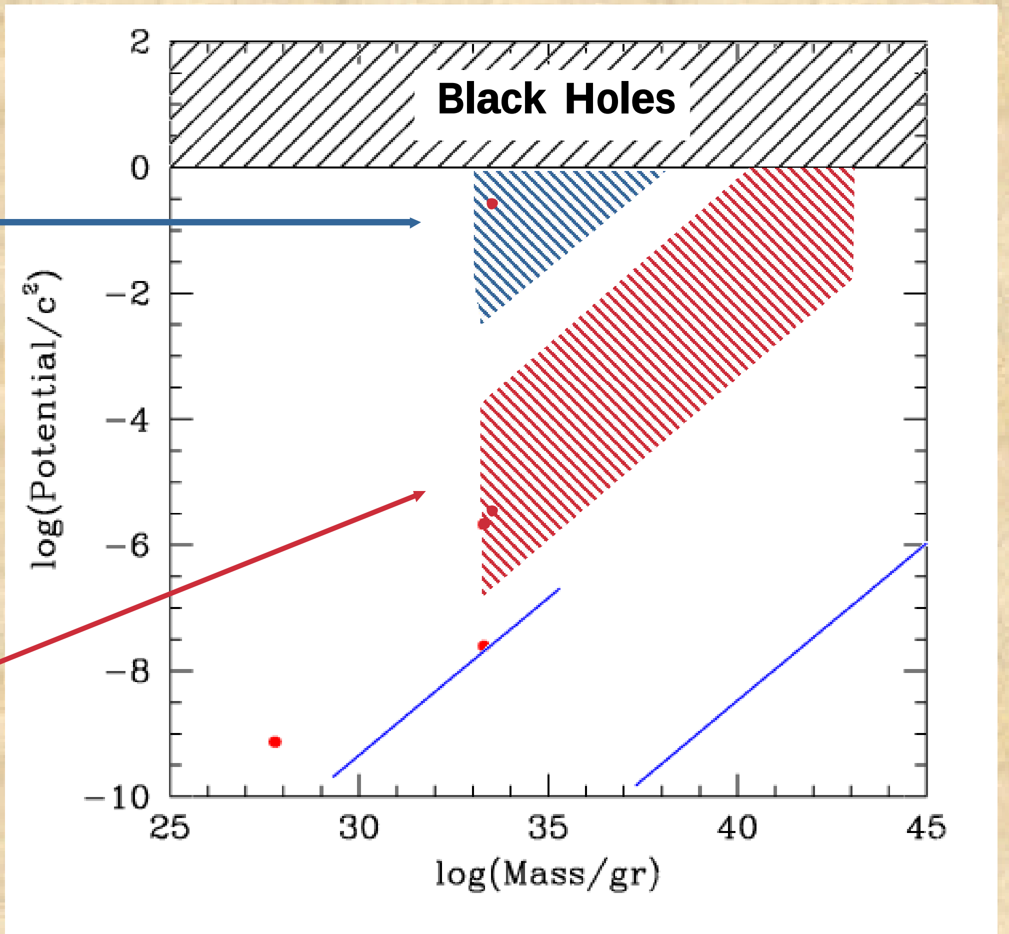
- Microlensing
- Strong Lensing
- Galactic Rotation Curves

GRAVITATIONAL WAVES AND GRAVITY TESTS

LIGO

LISA

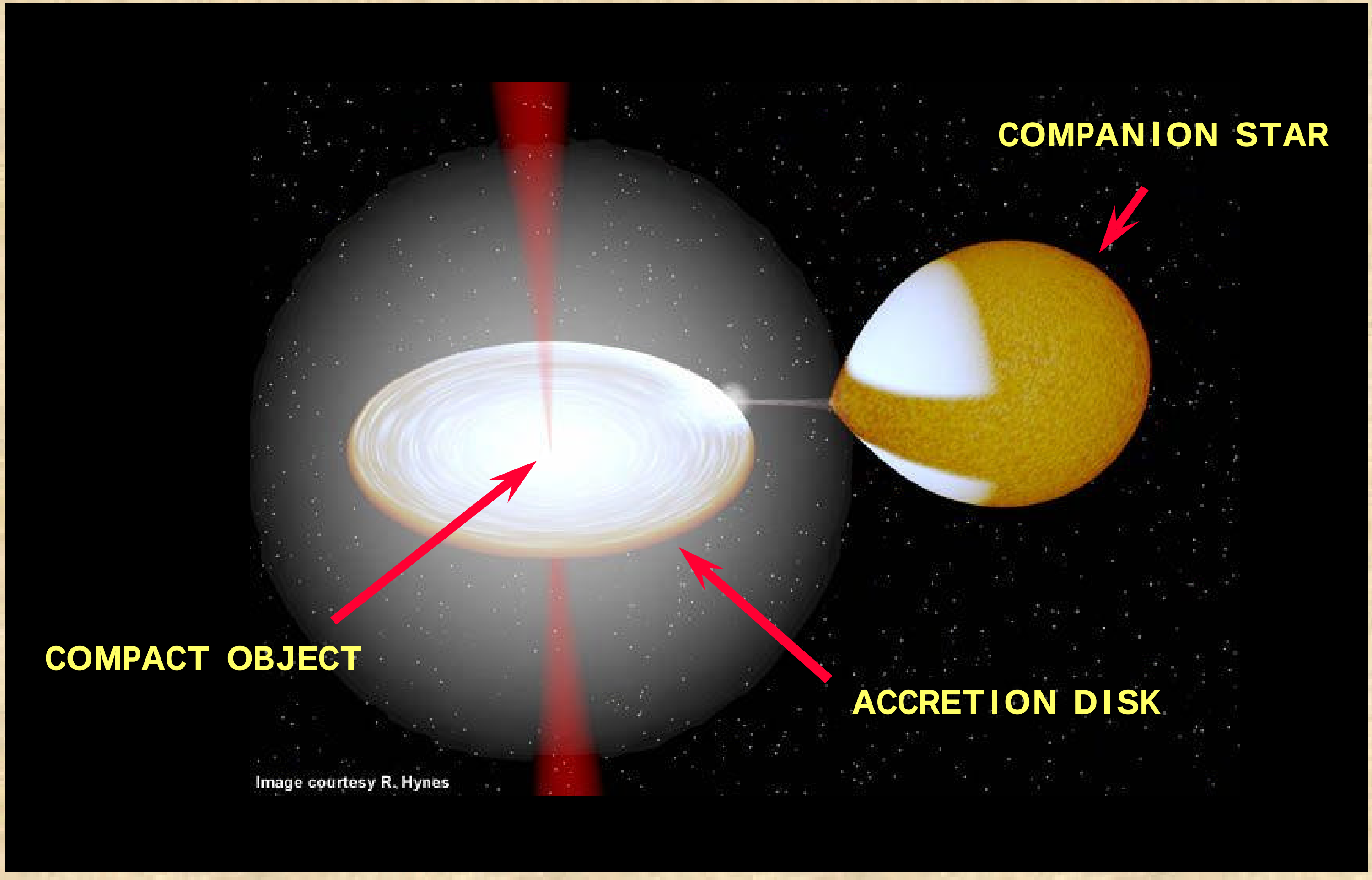




STRONG-FIELD TESTS DURING SHORT-LIVED FINAL STAGES OF COALESCENCE

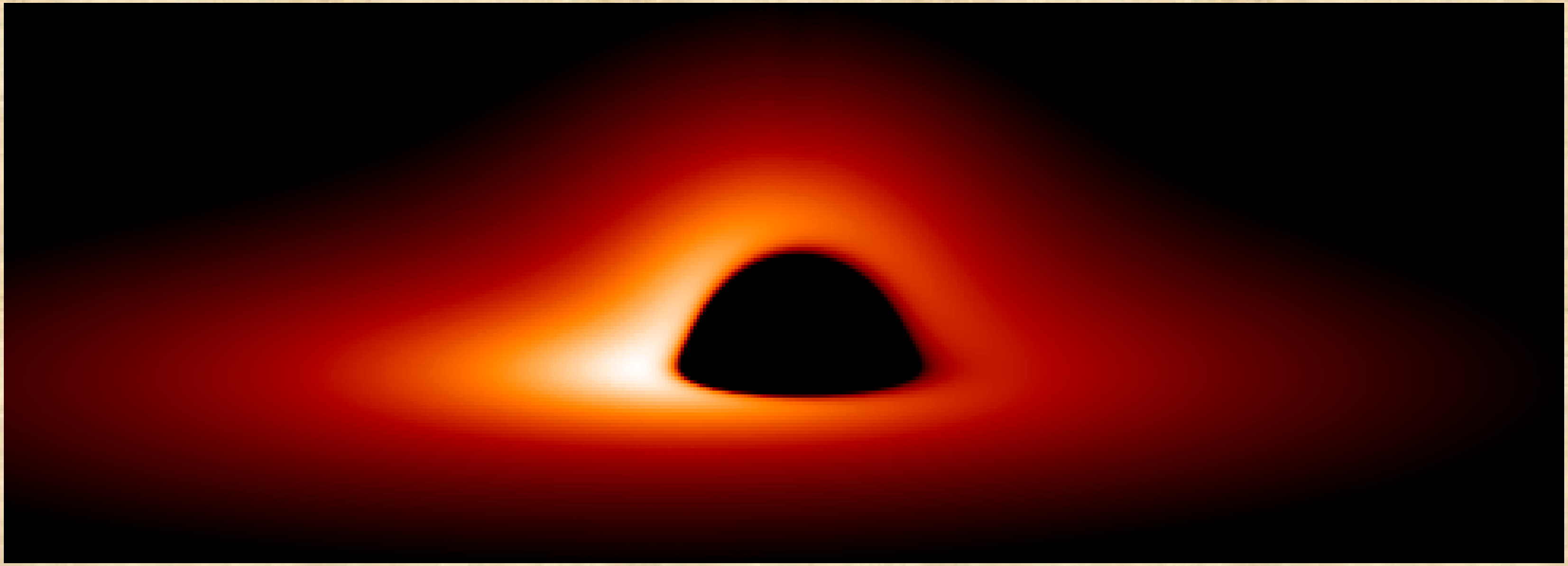
GRAVITY TESTS WITH HIGH-ENERGY PHOTONS

ACCRETING COMPACT OBJECTS:
PRIME CANDIDATES FOR RELATIVISTIC EFFECTS



PROBES OF GENERAL RELATIVISTIC EFFECTS

I. IMAGING OF SELF LENSING



C. REYNOLDS

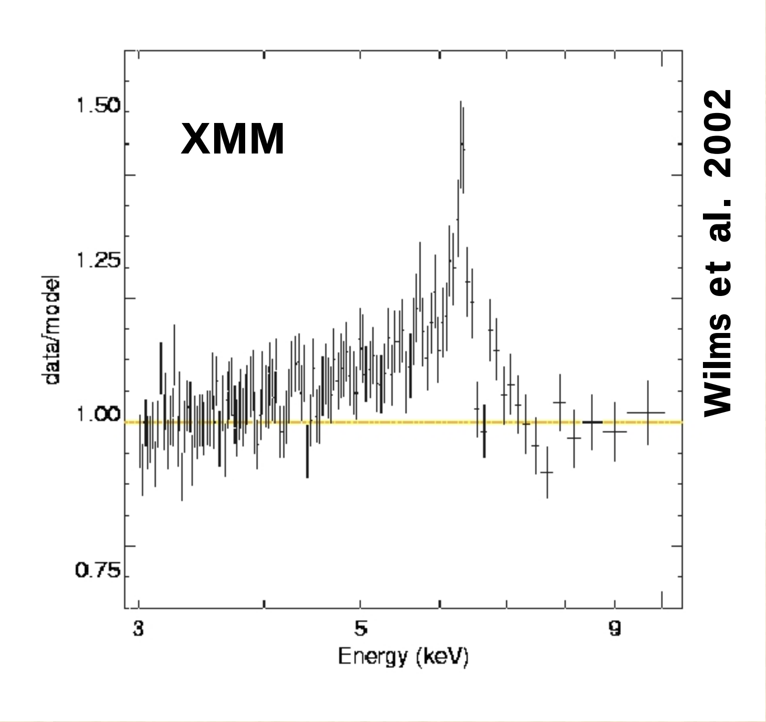
EVEN FOR ACTIVE GALACTIC NUCLEI REQUIRES
marcsec X-RAY INTERFEROMETRY:
THE BLACK HOLE IMAGER

II. SPECTROSCOPIC STUDIES OF REDSHIFTED LINES

XMM/Newton --- Chandra X-ray Observatory

REDSHIFTED LINES FROM INNER ACCRETION DISKS

BUT ACCRETION FLOWS ARE VERY TURBULENT!

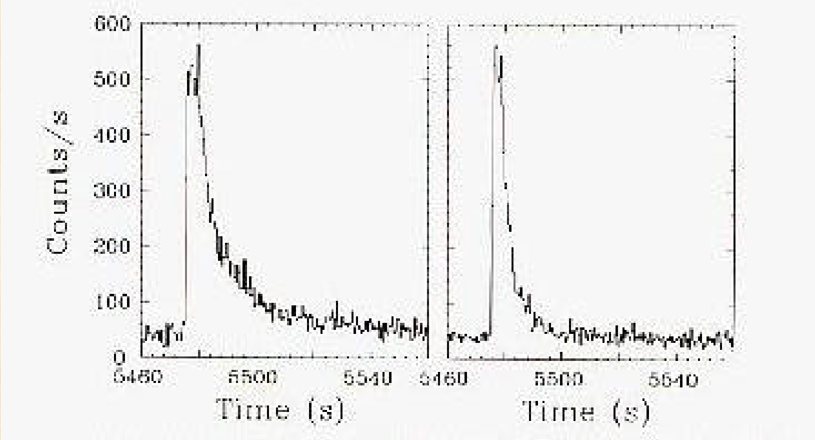


QuickTime™ and a YUV420 codec decompressor are needed to see this picture.

MCG 6-30-15

BUT Neutron Stars are Spherically Symmetric

(when slowly rotating)

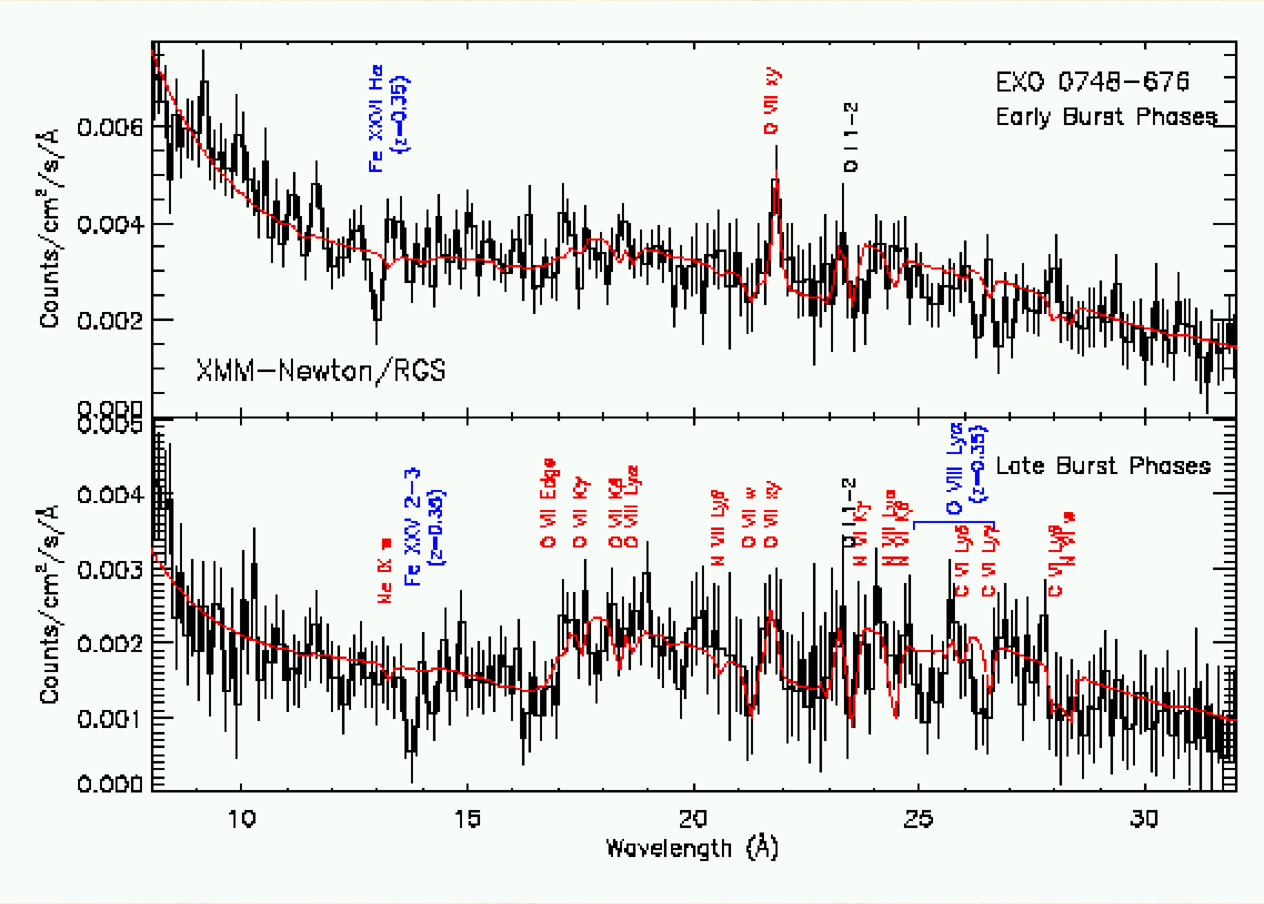


And Show Thermonuclear Bursts!

QuickTime™ and a BMP decompressor are needed to see this picture.

Spitkovsky et al. 2002

And show gravitationally redshifted lines!



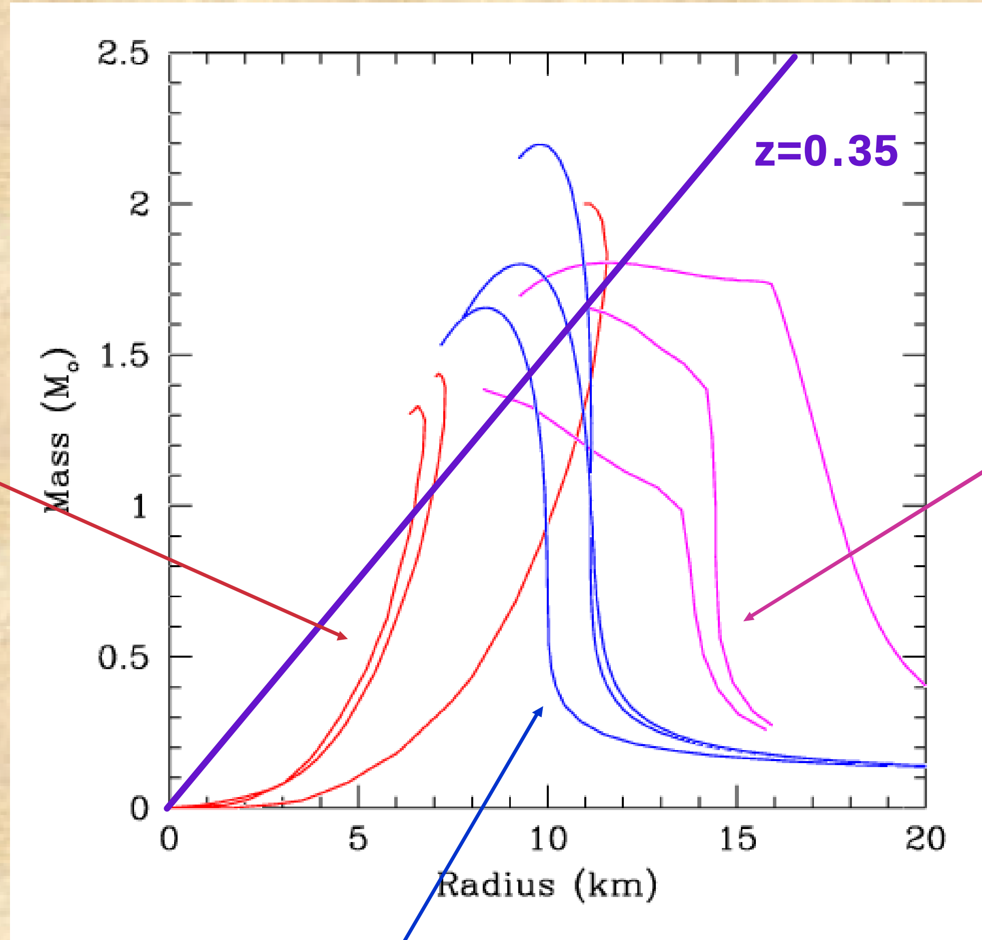
Cottam et al. 2002

Redshift for EXO 0748-676: z=0.35

In General Relativity:

$z=0.35$ Þ $M = 1.5\ (R/10\mathrm{km})\ M_\odot$

Strange Stars



Stars with condensates

Normal Neutron Stars

BUT NEUTRON-STAR STRUCTURE DEPENDS STRONGLY ON GRAVITY

A SIMPLE NEWTONIAN CALCULATION

For a polytropic equation of state:

$$P = K r^{1+\frac{1}{n}}$$

The radius of a star is:

$$R \sim \left[\frac{(n+1)K}{G} \right]^{n/(3-n)} M^{(1-n)/(3-n)}$$

EOS stiffness

EOS (in)compressibility

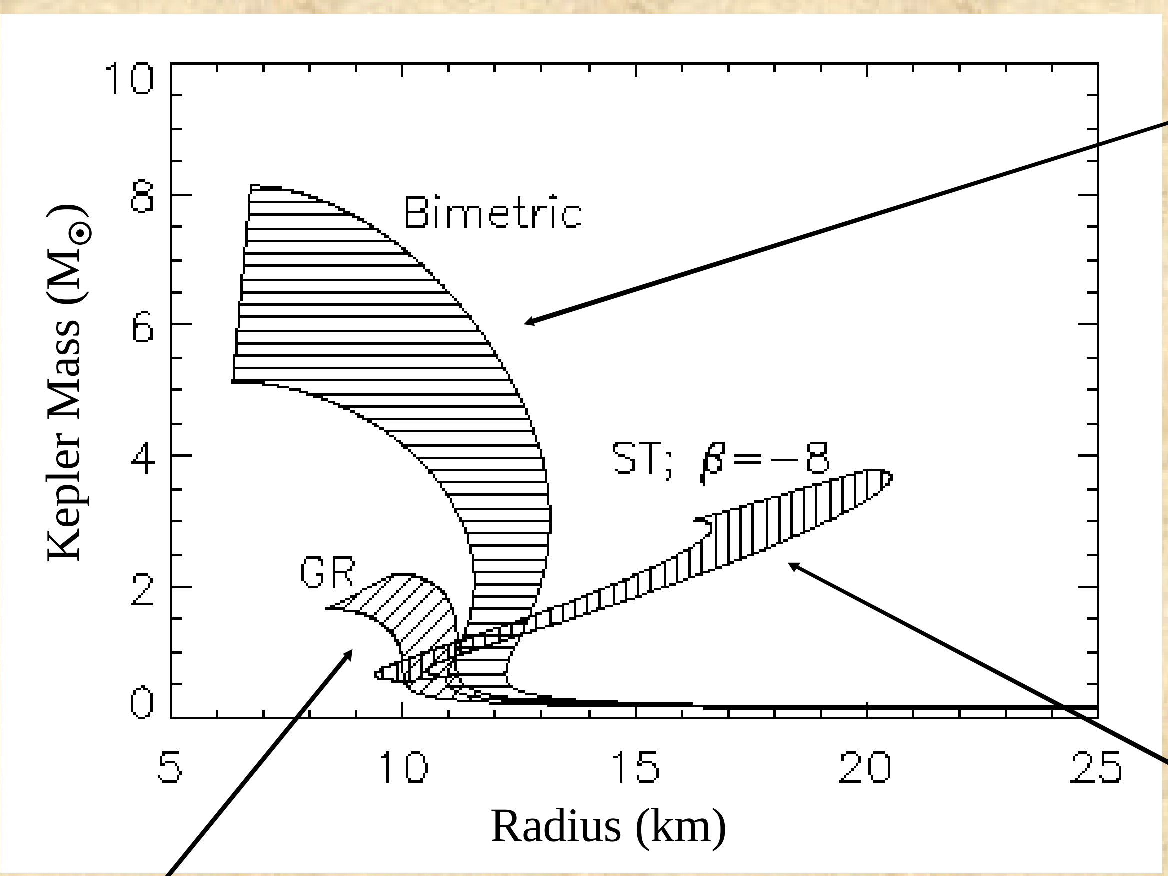
GRAVITY !

For most NS equations of state: n~1 Þ

$$R \sim \left(\frac{K}{G} \right)^{1/2} M^{0}$$

EOS AND GRAVITY ARE EQUALLY IMPORTANT

NEUTRON STARS IN THREE RELATIVISTIC THEORIES



Rosen's Theory

(prior geometry)

Scalar-Tensor (dynamical)

General Relativity

DeDeo & Psaltis 2003a

- **All theories consistent with solar system tests!**
- **Uncertainty due to gravity larger than EOS!**

GENERAL RELATIVITY HAS TWO INGREDIENTS

- The equivalence principle
- Einstein's equation

Ricci curvature

derived from the Hilbert action:

$$S = \frac{1}{16\pi G}\int d^4x\sqrt{-g}\left(R - 2\Lambda\right)$$

Cosmological constant

higher-order (R^2) Gravity:

$$\sqrt{-g}\left(R + aR^2 + \ldots\right)$$

or Gravity with additional fields, e.g., a scalar ϕ

$$\sqrt{-g}[R\,f(\phi) - V(\phi) - g^{\mu\nu}\partial_\mu\phi\,\partial_\nu\phi\,\omega(\phi)]$$

Parametrizing scalar-tensor gravity

$$S = \frac{1}{16pG_*}\int d^4x\sqrt{-\tilde{g}}\left[\tilde{R} - 2\tilde{g}_{mn}\P_m f \P_n f\right] + S_m\left[y, A^2(f)\tilde{g}_{mn}\right]$$

And parametrize the coupling function:

$$A(f) = A_0 e^{af + \frac{1}{2}bf^2 + \ldots} \quad \Big\} \quad A(f) = e^{\frac{1}{2}bf^2}$$

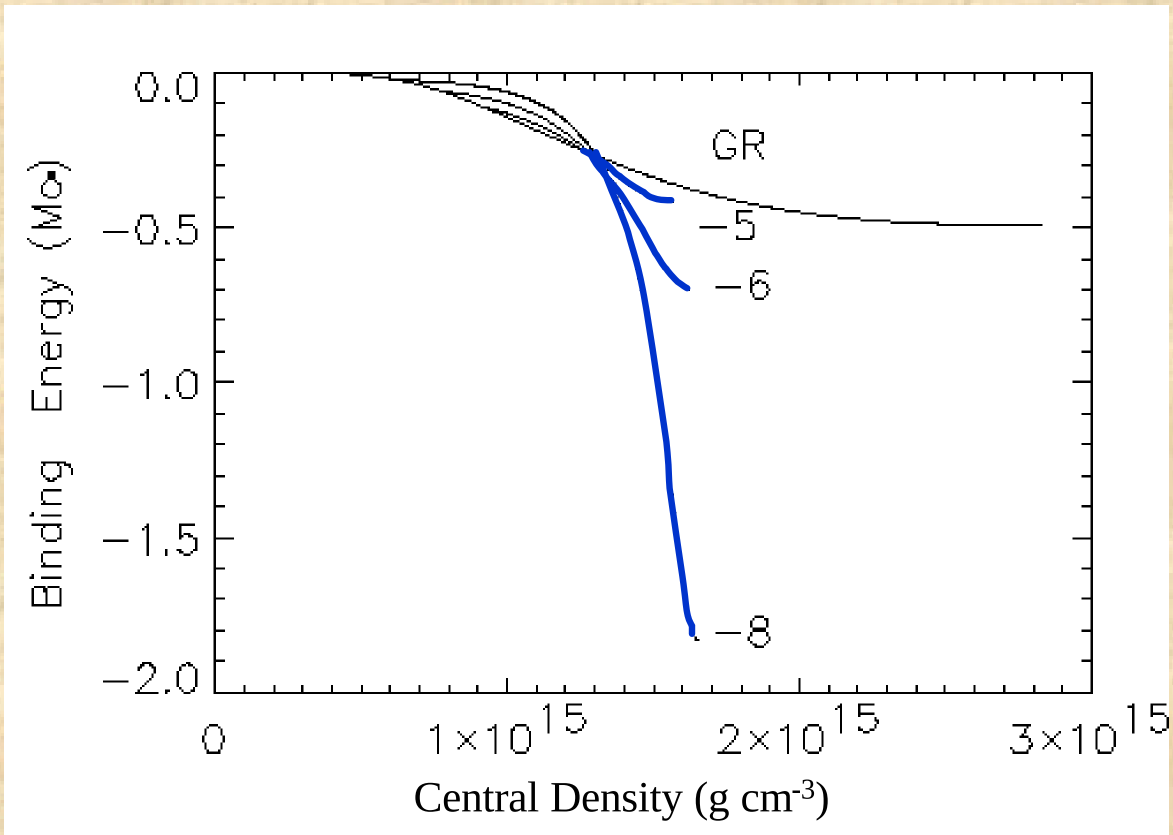
from weak-field tests: $A_0 = 1$ **and** $a \cong 0$

NEUTRON STARS IN SCALAR-TENSOR GRAVITY I

Double solutions; f=0 is always a solution!

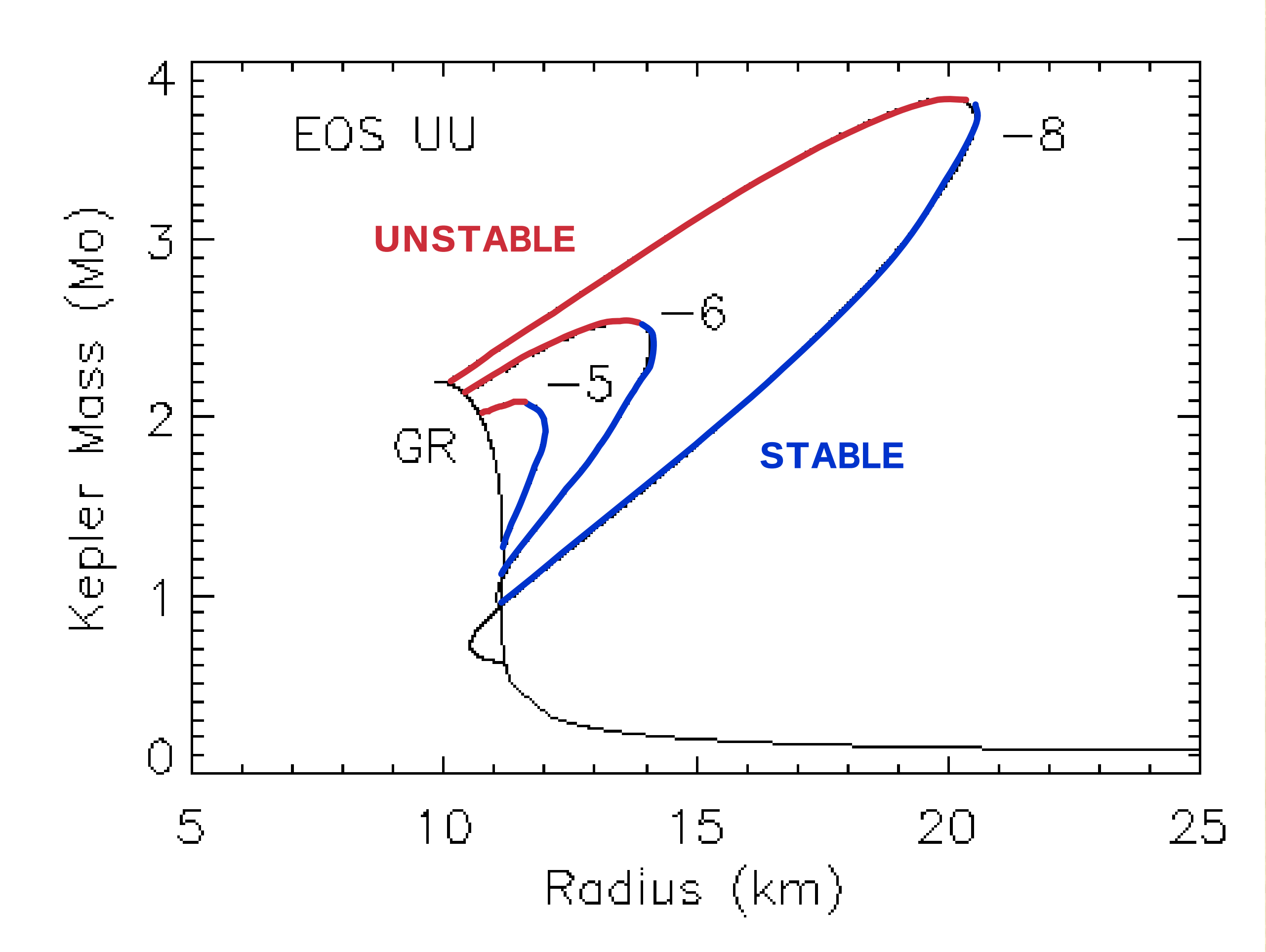
But for b<-4.85 Scalar Stars with f ¹ 0 are Energetically Favored!

Damour & Esposito-Farese 1993



DeDeo & Psaltis 2003b

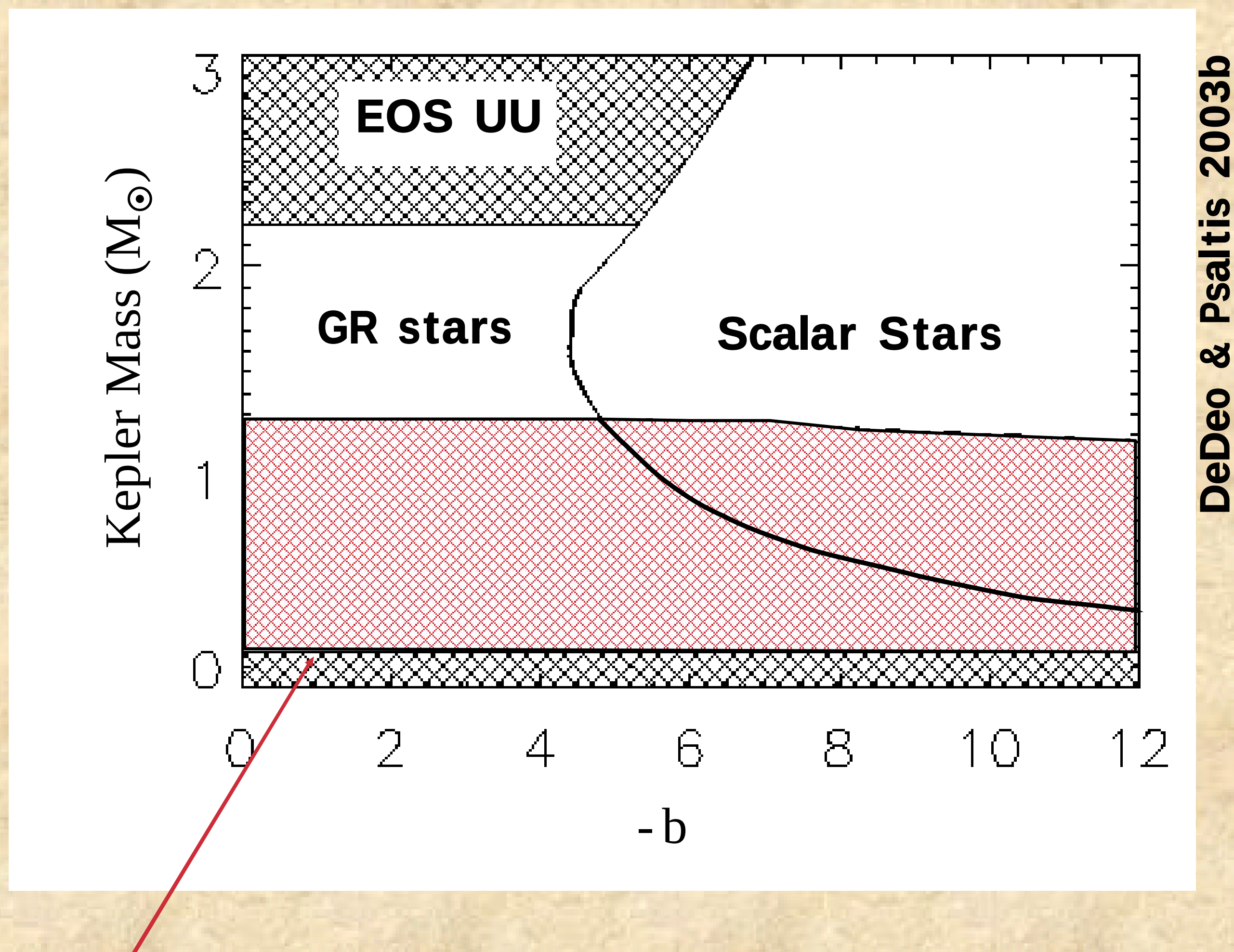
NEUTRON STARS IN SCALAR-TENSOR GRAVITY II



DeDeo & Psaltis 2003b

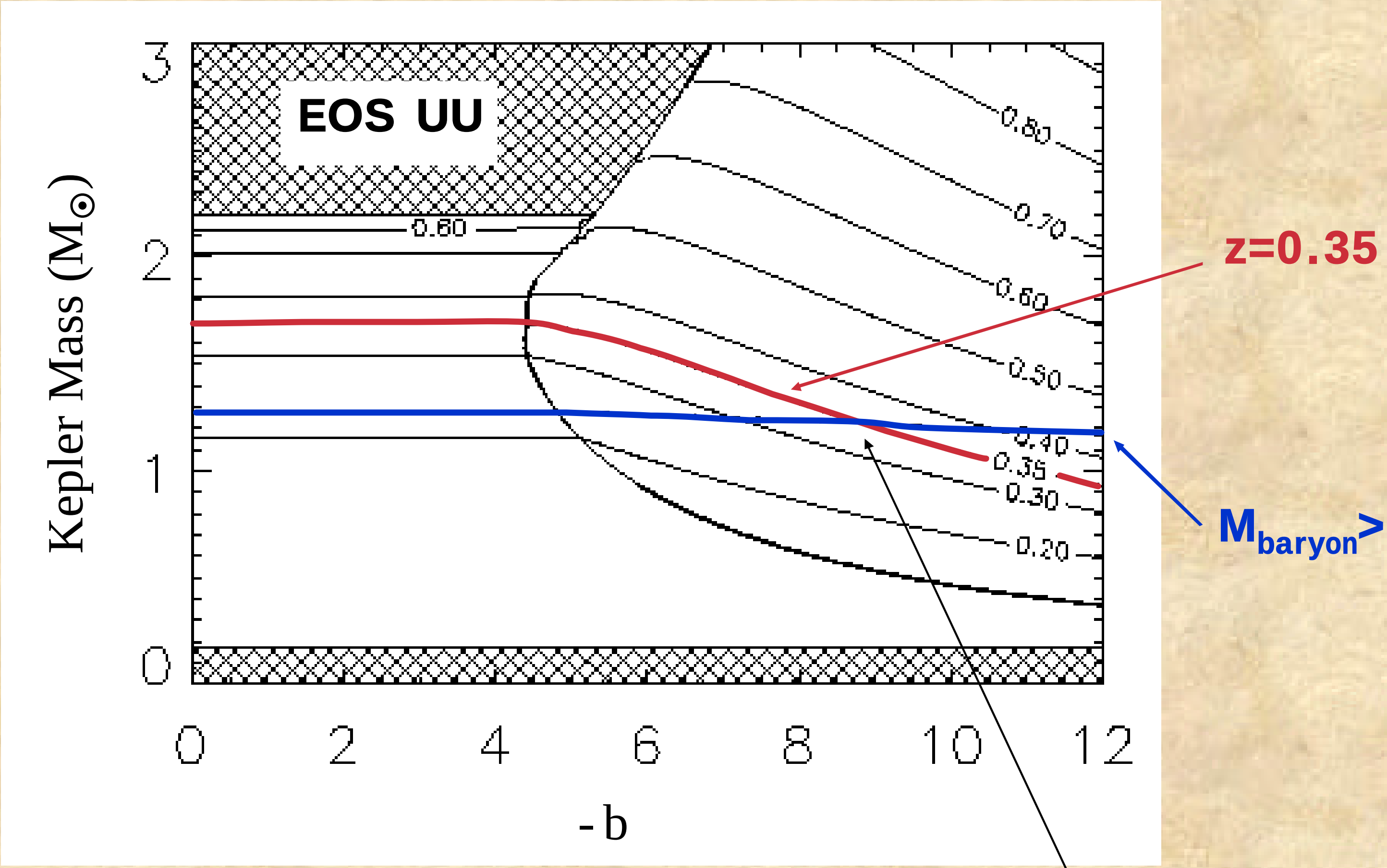
Scalar Stars can become Large and Massive

NEUTRON STARS IN SCALAR-TENSOR GRAVITY III



Baryonic Mass < $1.4M_\odot$

LIMITS FROM GRAVITATIONAL REDSHIFTS

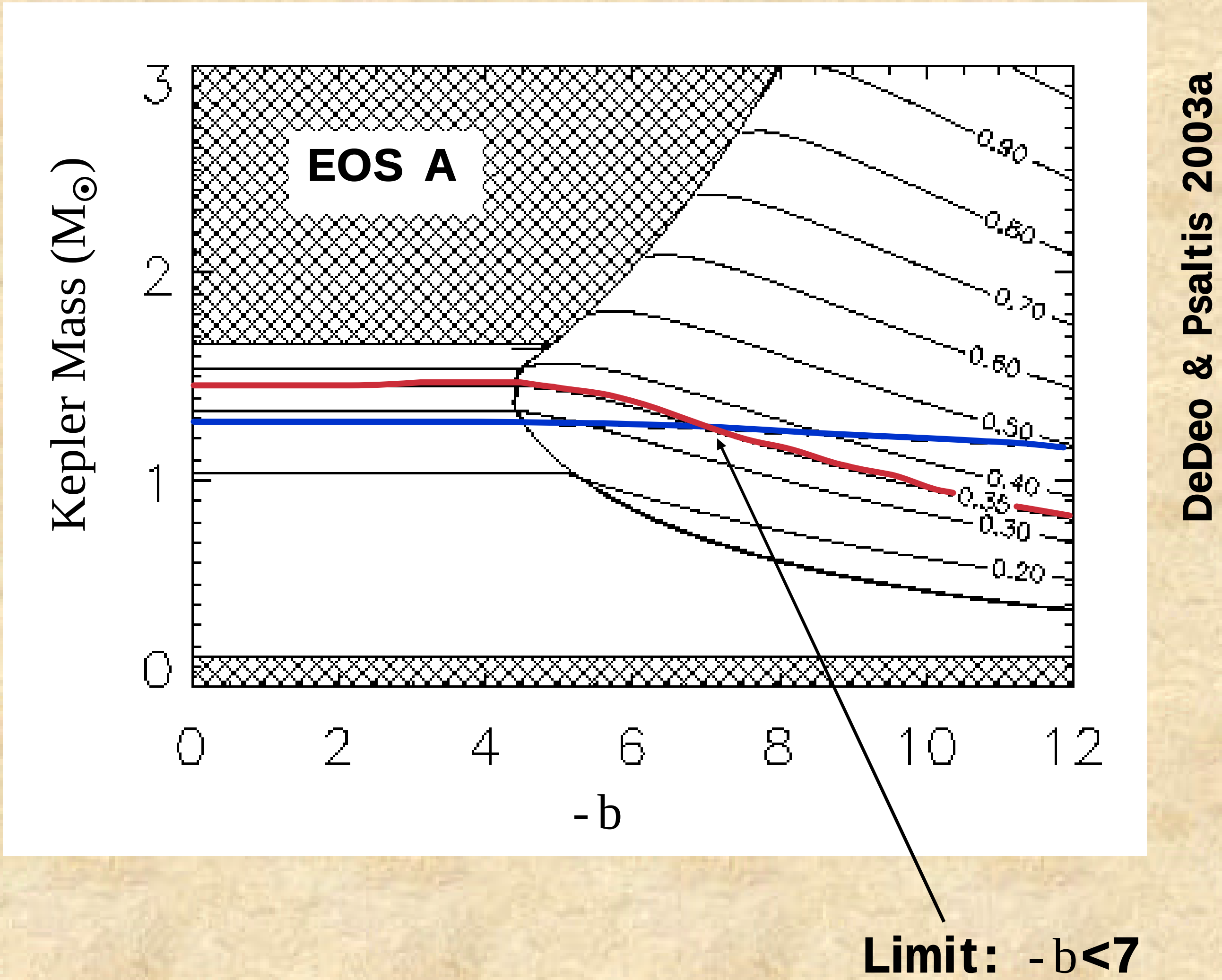


DeDeo & Psaltis 2003a

Limit: -b<9

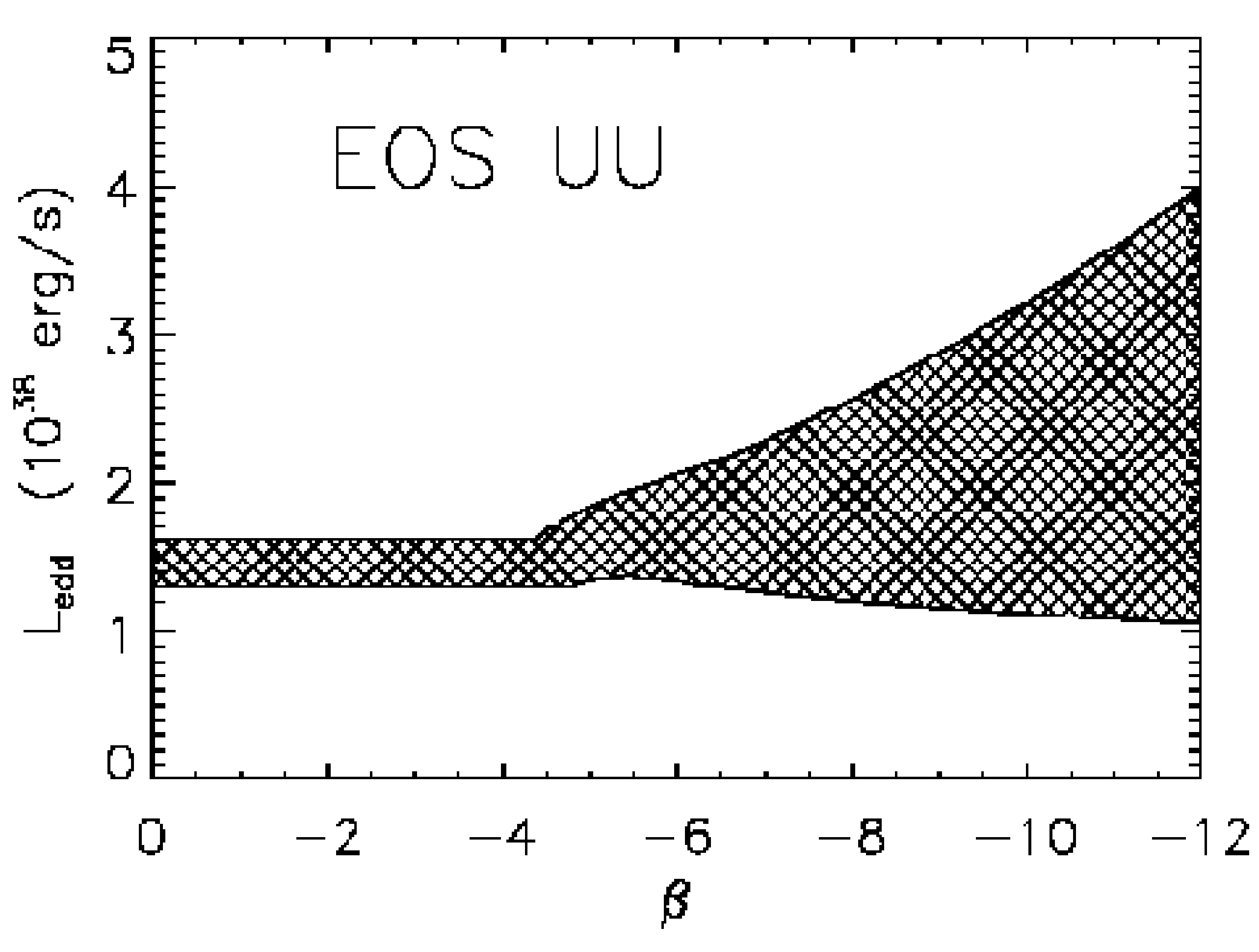
If the mass of EXO 0748-676 is measured, limits will become tighter

LIMIT DEPENDS WEAKLY ON EQUATION OF STATE



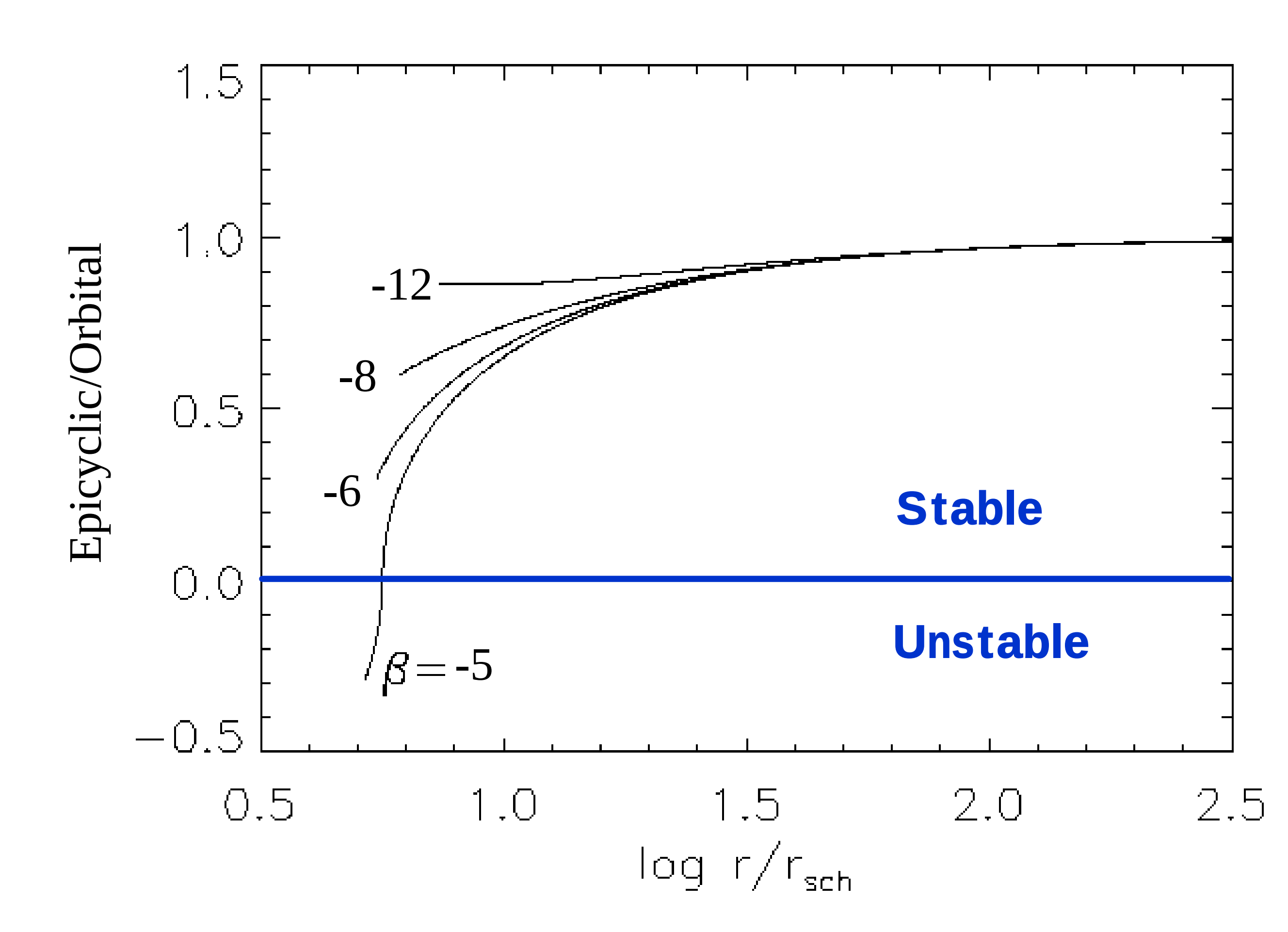
Inside the neutron star: $f \leq 0.05 \Rightarrow A(f) = e^{\frac{1}{2}bf^2} \approx 1 - 0.01$

THE EDDINGTON LIMIT FROM ACCRETION/BURSTS ON NEUTRON STARS



DeDeo & Psaltis 2003c

THE EXISTENCE OF UNSTABLE ORBITS



DeDeo & Psaltis 2003b

In some relativistic gravities, all orbits are stable!

CONCLUSIONS

(I) Gravity in the Strong-Field Regime has not been tested

(II) Masses and Radii of Neutron Stars are significantly affected by gravity

$\Rightarrow$ **a great laboratory to perform gravitational tests**

(III) Recent observation of atomic redshifted lines places strong constraints on scalar-tensor gravity theories:

$$-\beta < 7-9$$